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SPREAD SPECTRUM COMMUNICATION NETWORKS

FINAL REPORT

submitted by

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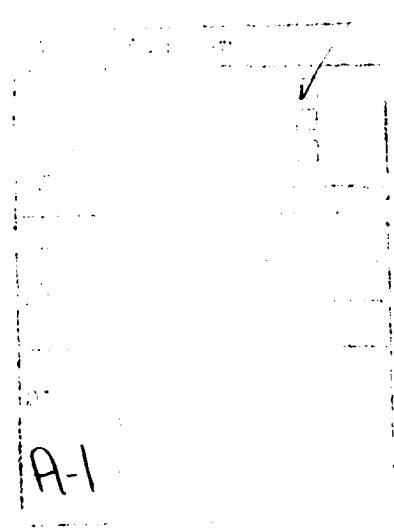
This is the final report for the research program titled *Spread Spectrum Communication Networks* which was supported by the U. S. Army Research Office under Contract DAAL03–87–K–0097 (Proposal Number 25342–EL) for the period August 15, 1987 through January 31, 1991. The research was carried out at the University of Illinois at Urbana-Champaign under the direction of Professors Michael B. Pursley and Dilip V. Sarwate who were the principal investigators for the contract.

Statistical Dependence of Hits in Frequency-Hop Communication

One of the difficulties that arises in the analysis of codeword and packet error probabilities in asynchronous frequency-hop (FH) multiple-access communication systems and networks is the statistical dependence between symbol errors within a codeword or packet in FH communications with multiple symbols per dwell interval. The basic problem is that the hits by other transmissions are statistically dependent. In one paper [36], we developed improved bounds on the codeword error probability for such FH multiple-access systems and networks. This was accomplished by investigating models in which hits are conditionally independent given the number of interfering packets and choosing the conditional probability of a hit in such a way that a bound on the performance of the actual system can be obtained. We showed that if the ratio of the number of interfering packets to the number of frequency slots is held constant, hits in the asynchronous FH network are asymptotically independent in the limit as the number of frequency slots increases. Thus, when the number of frequency slots is large, the error probabilities can be closely approximated by using the simplified model with independent hits. We published a related paper [18] which shows that, contrary to a paper published by another author, the sequence of hits in an asynchronous FH multiple-access communication system does not form a Markov process.

Asymptotic Multiple-Access Capability of Frequency-Hop Communications

Another investigation focused on the asymptotic multiple-access capability of asynchronous FH communications [14,26]. Our results depend only on the convergence in distribution of N_{max}/ρ and N_{min}/ρ as the offered traffic ρ increases, where of N_{max} and N_{min} are the maximum and minimum number of packets in the interval for unslotted FH packet transmission. Our results shed light on the modeling and analysis of unslotted transmission in packet radio networks for both

fixed-length and variable-length packets. We show that the asymptotic sum capacity of the unslotted system can be attained by use of Reed-Solomon codes.

Universal Communication Receivers

We conducted research on universal communication receivers, with emphasis on parallel architectures that can cope with uncertainty in channel characteristics [30]. The parallel implementation consists of a finite number of receivers with the property that, for any channel in the class of interest, the performance of at least one of the receivers will be within a specified degradation of the optimal performance. The identification of the good receiver is accomplished by means of side information generated by an appropriate coding scheme. We have obtained sufficient conditions on the channel classes to ensure a universal design of the parallel type is possible. We have also outlined procedures for carrying out the design, and we have given a general example for M-ary signaling as a specific application. We have shown that Reed-Solomon codes with bounded distance decoding satisfy the requirements of a good coding scheme for our application [39].

Direct-Sequence Spread Spectrum Communication with Linear Distortion

In another phase of the research, we investigated the performance of direct-sequence (DS) spread spectrum when subjected to linear distortion, including that due to bandwidth limitations, gain variations across the passband, and nonlinear phase characteristics of amplifiers and receivers. We were primarily interested in obtaining quantitative results on the effects of linear distortion on the multiple-access capabilities of DS spread-spectrum communications.

Whereas previous investigations of the multiple-access capability of DS spread spectrum are based on ideal pulse shapes for the chip waveforms (e.g., rectangular pulses for PSK or half sine-wave pulses for MSK), our approach is to consider the actual chip waveforms that arise from various types of filtering operations on the DS spread-spectrum signal. Our model includes a filter to represent the channel filtering, which includes the filtering due to the propagation medium, the RF filtering in the transmitter and receiver front end, and the IF filtering in the receiver. The model also includes a filter to represent the baseband filtering in the receiver.

Our approach is a combination of analysis and computer-aided analysis. In particular, we have combined analytical methods based on the signal-to-noise ratio that we introduced in 1977 with computer techniques for modeling and analyzing

the filtering operations. A wide range of software tools have been developed to carry out this modeling and analysis task [17,27].

The first step was carried out by Uetrecht [17], who examined the effects of linear filtering on the performance of a DS spread-spectrum communication system with a single transmitted signal. The results of this work permit a tradeoff between the system performance and the type, complexity (i.e., order), bandwidth, and amplitude ripple for the filters in the system. The channel filter for this study is selectable (Butterworth and Chebyshev filters were considered for the numerical results), and the receiver filter is a correlation receiver with either an ideal integrator or a suboptimal low-pass filter. The effects of variations in the amplitude and nonlinearities in the phase of the transfer functions of the channel and the receiver were evaluated. The issue of accounting for filter delay in the chip and bit synchronization was also considered in this work.

The results are generally presented in graphs of the degradation as a function of $\eta = (BT_c)^{-1}$, the inverse of the time-bandwidth product, where B is the 3 dB bandwidth of the channel filter and T_c is the chip duration. If the receiver has an ideal integrator and the channel filter is a Chebyshev filter, the degradation reaches 3 dB for η in the range 0.9 to 1.3, with the smaller values of η corresponding to the 11-pole filter and the larger values corresponding to the 3-pole filter. The 7-pole filter gives a degradation of 3 dB at $\eta = 1$ ($BT_c = 1$). If the receiver baseband filter is a Butterworth filter, the range of η for a 3 dB degradation is about 0.8 to 1.1, and the 7-pole filter gives a degradation of 3 dB at $\eta = 1.1$ (B $T_c = 0.9$). For many applications, a 3 dB degradation is too large, and so the inverse time-bandwidth products will have be smaller than these ranges. As another example of the numerical results, $\eta = 0.5$ ($BT_c = 2.0$) gives a degradation of less than 1 dB for all Chebyshev filters (3, 5, 7, 9, and 11-pole) if the integrator is used as a baseband filter, and it gives a degradation of between 1 dB and 1.5 dB if the Butterworth baseband filter is used.

All of the results quoted so far are for the rectangular chip waveform, but numerical results were also obtained for the sine pulse as a chip waveform (e.g., for MSK chip modulation). Generally, the degradations are comparable for the two chip waveforms, but the degradations are slightly smaller for sine chip waveform if the time-bandwidth product is large, and and they are 1 dB or so smaller for the rectangular chip waveform if the time-bandwidth product is small. The sensitivities of the degradation to the choice of spreading sequence and the filter amplitude ripple. As expected, the degradation is nearly independent of the choice

of spreading sequence for large time-bandwidth products, but it is extremely sensitive to the choice of spreading sequence if the time-bandwidth product is less than 1.0 (variations in degradation of as much as 3 dB were discovered).

The second step was carried out by Johnson [27], who examined the effects of linear filtering on the multiple-access capability of DS spread spectrum. Analytical results from our past work describe the effects of multiple-access interference for systems with ideal all-pass channels. The work of Johnson gives corresponding results for systems with more realistic channel filtering, and it permits tradeoffs to be made between the degradation and the filter parameters. The degradation in multiple-access capability due to bandlimiting, amplitude ripple, and nonlinear phase characteristics have been determined. Generally, we find that the variance of the multiple-access interference at the *output* of the baseband filter decreases by about a factor of two as the time-bandwidth product decreases from C to 0.5. This is combined with the effects of the filtering on the noise and multiple-access interference to obtain the overall performance of the spread-spectrum multiple-access system.

Concatenated Coding for Frequency-Hop Radio Systems and Networks

We completed an investigation of the performance of concatenated coding for FH radio systems and networks [41]. In this study, Reed-Solomon outer codes and convolutional inner codes are employed to combat the effects of thermal noise and partial-band jamming. The jamming is modeled as partial-band Gaussian noise, and the frequency band that it occupies ranges from zero to the full band of the FH signals. Upper bounds on the packet error probability were derived and employed to perform tradeoff studies involving the rates of the outer and inner codes, the constraint length of the convolutional code, and the number of codewords per packet. It was found that the best Reed-Solomon codes were typically of high rate, and rate 1/2 convolutional codes were typically better than the rate 1/3 or 3/4 codes. The optimum number of codewords per packet is approximately 20 in all cases we examined. So far in this investigation, it has been assumed that no side information is available; a topic for future study is the use of side information to improve the performance of concatenated coding in FH radios.

In the most recent work on concatenated coding for FH radio systems and networks that will permit us to strengthen our results. Using some recent results on the symbol error probability for convolutional codes with Viterbi decoding, we

believe that we can obtain very tight bounds on the codeword error probability for the Reed-Solomon codes used in the concatenated coding scheme. This in turn will lead to a very good approximation of the bit error probability. Previously, the only results were upper bounds on the packet error probability. As a result of these recent developments, we are currently revising the paper and will resubmit it soon.

Pseudocyclic Maximum-Distance-Separable Codes

We obtained new results on pseudocyclic maximum-distance-separable (MDS) codes over finite fields with q elements, and have succeeded in completely characterizing such codes for all block lengths n which are divisors of either q+1 or q−1. In particular, the only pseudocyclic MDS codes of length q−1 are the well-known cyclic Reed-Solomon codes. Details have been published in [32].

Decoding Algorithms for BCH and Reed-Solomon Codes

We have discovered that BCH and Reed-Solomon decoders based on the Peterson-Gorenstein-Zierler algorithm occasionally produce output vectors that are not codewords at all. Decoders based on the Euclidean greatest common divisor algorithm also exhibit this behavior, but with different error patterns. Standard decoders based on the Berlekamp-Massey algorithm do not seem to exhibit this behavior, but certain high-speed decoders do. This type of behavior has been named a decoder malfunction, and we have characterized the error patterns which cause the decoders to malfunction. We have discovered a simple test that allows a decoder based on the Euclidean algorithm to avoid malfunctions. The results have been published in [33].

We have studied the Euclidean algorithm for decoding BCH and Reed-Solomon codes, and have developed a variation of this algorithm which can be used for decoding interleaved codes. In contrast to the usual behavior of the Euclidean algorithm which uses i iterations when decoding a codeword with i errors, the variant algorithm has the useful property that all the codewords comprising an interleaved codeword are decoded in 2t iterations regardless of the number of errors in the individual codewords. Both the original Euclidean algorithm and the modified algorithm use the same number of Galois field multiplication and addition operations for decoding any given received vector: it is just that the modified algorithm spreads the computational task evenly over 2t iterations. Also, in the variant algorithm, all intermediate polynomial multiplications are effectively simplified to the multiplication of a polynomial by a

scalar, i.e. a constant. These properties help in reducing the complexity of the decoder and have interesting implications for VLSI implementations. Details can be found in [23]

Continuous Phase Modulation for Direct-Sequence Signaling

In contrast to several proposed continuous phase modulation (CPM) schemes for DS signaling, the scheme that we have investigated maintains phase continuity across bit boundaries. The power spectrum for these signals has been obtained analytically, and programs have been written to evaluate the spectral characteristics for various signal designs. We have found necessary and suffiicient conditions on the signature sequences for the power spectrum of a spread-spectrum CPM signal to contain discrete components (delta functions). For the case of binary signature sequences, such discrete componnets occur if and only if all the signature sequences have the same Hamming weight. Discrete power spectral components make it easier to detect a signal, thus reducing its LPI and anti-jam capabilities. Another disadvantage of the use of signature sequences of identical Hamming weight is that there is no memory from symbol interval to symbol interval in the spread-spectrum CPM signal. Consequently, the bit error rate achieved by such signaling can be no better than that achieved by traditional direct-sequence spread-spectrum signaling. Fortunately, it is very easy to avoid creating a spread-spectrum CPM signal with discrete power spectral components.

We have also studied optimum and suboptimum receivers for direct-sequence CPM signals. The optimum receiver for such signals is a Viterbi detector whose error performance is characterized by the minimum Euclidean distance between the signals if the signal-to-noise ratio (SNR) is large. Our results show that spread spectrum CPM can achieve larger minimum distances than traditional CPM, and thus can perform better than traditional CPM in the limiting case of large SNR. In contrast, spread-spectrum PSK and narrowband PSK have the same error probability for any given SNR. We have also considered the case when the SNR is small and the optimum receiver performance is difficult to evaluate. In order to obtain an upper bound on the performance for this case, we have considered a suboptimum receiver which observes the signal for a finite length of time only. Upper bounds have been obtained analytically on the error probability achieved, and numerical evaluation of these bounds has been carried out. Details are reported in [28] and a journal article is being prepared for publication.

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	D. J. Taipale, Ph. D. in Electrical Engineering

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